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IGNITION AND DENTONATION CHARACTERISTICS OF HYDROGEN AND HYDROCARBON FUELS IN A PDE

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Combustion Branch
Turbine Engine Division

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Over the past two decades, several fuels have been tested in pulsed detonation engines (PDEs) throughout the world. This research focuses on developing a baseline set of ignition and detonation performance measures for six distinct fuels in air: Hydrogen, ethylene, propane, aviation gasoline (avgas), JP-8, and Fischer-Tropsch JP-8 (S-8). To quantify the ignition and detonation performance, four parameters are examined: Ignition time, deflagration- to-detonation transition (DDT) time, DDT distance, and the upper Chapman-Jouguet (CJ) wavespeed. Those four parameters are presented as a function of equivalence ratio from lean to rich flammability limits for all six fuels. Hydrogen was found to have the best ignition and detonation characteristics, followed by ethylene. Propane, avgas, JP-8, and S-8 exhibited similar ignition and detonation characteristics, as expected based on cell size. Minimum ignition times for all fuels occurred near an equivalence ratio of 1.3, while the minimum DDT times and distances occurred between equivalence ratios of 1.1 and 1.2. All experimental CJ wavespeeds were within 5% of the theoretical CJ wavespeed with the exception of hydrogen, which was systematically between 6% and 8% lower than the theoretical value.

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Ignition and Detonation Characteristics of Hydrogen And Hydrocarbon Fuels in a PDE

Over the past two decades, several fuels have been tested in pulsed detonation engines (PDEs) throughout the world. This research focuses on developing a baseline set of ignition and detonation performance measures for six distinct fuels in air: Hydrogen, ethylene, propane, aviation gasoline (avgas), JP-8, and Fischer-Tropsch JP-8 (S-8). To quantify the ignition and detonation performance, four parameters are examined: Ignition time, deflagration to detonation transition (DDT) time, DDT distance, and the upper Chapman-Jouguet (CJ) wavespeed. Those four parameters are presented as a function of equivalence ratio from lean to rich flammability limits for all six fuels. Hydrogen was found to have the best ignition and detonation characteristics, followed by ethylene. Propane, avgas, JP-8, and S-8 exhibited similar ignition and detonation characteristics, as expected based on cell size. Minimum ignition times for all fuels occurred near an equivalence ratio of 1.3, while the minimum DDT times and distances occurred between equivalence ratios of 1.1 and 1.2. All experimental CJ wavespeeds were within 5% of the theoretical CJ wavespeed with the exception of hydrogen, which was systematically between 6% and 8% lower than the theoretical value.

Nomenclature

E_{crit}	=	**Critical Initiation Energy**
λ	=	**Cell Size**

Introduction

THE potential for higher thermal efficiencies, high thrust, low weight, low cost, scalability, and a large operational envelope has driven pulsed detonation engine (PDE) research over the last two decades[1-3]. The potential for higher thermal efficiency is based on the understanding that the constant volume process that occurs in a pulse detonation engine creates less entropy than the constant pressure process that occurs in most modern gas turbine engines[4]. Due to the pulse detonation engine's attractive qualities it has received attention by many facets of the aeronautical engineering community; spawning interest in several applications for the PDE including aircraft, spacecraft, cruise missiles, and hybrid functions with a gas turbine engine, ramjet, or scramjet.

To quantify the ignition and detonation characteristics of the fuel/air mixtures, three key performance parameters were examined. The parameters are the time from spark deposition to the creation of a deflagration wave within the fuel/air mixture (ignition time), the time to transition the deflagration wave into a detonation wave (DDT time), and the length of detonation tube required for the mixture to transition to a detonation (DDT distance). In addition to the three aforementioned parameters, the upper Chapman-Jouguet (CJ) wavespeeds of the fuels were experimentally determined for each of the fuel air mixtures. .

This research was completed to establish a baseline of ignition and detonation characteristics of a PDE fueled with a large spectrum of conventional fuels in air; specifically, hydrogen, ethylene, propane, aviation gasoline (avgas), JP-8, and S-8[*]. These fuels were selected because they represent a large spectrum of PDE fuels. Prior to this research, substantial data on ignition time, DDT time, DDT distance and CJ wavespeed was published[6-12], but it is scattered over several papers. Additionally, the previous data was gathered using different experimental setups, making comparison between the data set rather questionable. Schauer et al.[6] experimentally measured the CJ wavespeeds for mixtures of propane, avgas, JP-8, and JP-10 in air as a function of equivalence ratio using a similar setup to this research. Schauer et al.[6] were only marginally successfully in detonating propane, due to issues with

[*] S-8 is a synthetic fuel derived from natural gas via the Fischer-Tropsch process[5]. S-8 is also referred to as Fischer-Tropsch JP-8 or simply Fischer-Tropsch.

the fuel supply system. Tucker et al.[7,8] measured the ignition time, DDT time, and CJ wavespeed as a function of equivalence ratio for mixtures of avgas, JP-8, iso-octane, and heptane in air using a fuel flash vaporization system to heat the fuel prior to injection into the air. Card et al.[9] determined the DDT distance for mixtures of hydrogen, ethylene, acetylene, and JP-10 in air as a function of equivalence ratio in a 10 cm diameter tube. Card et al.[9] defined the DDT distance as the length were the wavespeed jumps from the isobaric speed of sound of the products to the CJ wavespeed. Ciccarelli and Card[10] examined the wavespeed of JP-10/air mixtures at elevated temperatures and pressures. Akbar et al.[10] measured the wavespeeds of unsensitized and sensitized mixtures of JP-10 and Jet-A. Austin and Shepard[12] measured the wavespeed of JP-10/air mixtures as a function of equivalence ratio in a 280 mm diameter tube.

Background and Theory

Previous experimental research[6] has shown that a typical stoichiometric low vapor pressure liquid hydrocarbon/air mixture requires on the order of 10^5 J of energy to directly initiate detonation (critical initiation energy), six orders of magnitude greater than the energy available form a typical spark plug (~100 mJ). Thus a mixture with low critical initiation energy is more susceptible to DDT. Knystautas et al.[13] and Schauer et al.[6] independently developed correlations for the detonation cell size (λ) of a mixture and the critical initiation energy of a mixture, where the critical initiation energy varies with the cube of the detonation cell size (Equation 1). Therefore, a decrease in detonation cell size is an indication of greatly improved detonability. Schauer et al.[5] developed the correlation based on data compiled by Kaneshige and Shepherd[14].

$$E_{crit} \propto \lambda^3 \tag{1}$$

The detonation cell size is a physical characteristic of a detonation wave, shown in Fig 1. A more detailed discussion on detonation cell structure can be found in Fickett and Davis[15]. Figure 2 is a plot of detonation cell size as a function of equivalence ratio for hydrogen, ethylene, propane, JP-4, and JP-10. JP-4 and JP-10 are liquid hydrocarbon fuels that are on the same order of density as avgas, JP-8, and S-8. The hydrogen data demonstrates the smallest detonation cell size of the fuel presented. As will be shown, the smaller cell size directly translates to better ignition and detonation performance. Ethylene demonstrates the next larger cell sizes, which will be shown later to translate to the second best ignition and detonation performance. The propane, JP-4, and JP-10 show similar detonation cell sizes, indicating that avgas, JP-8, and S-8 exhibit similar ignition and detonation characteristics to propane. The data from Fig. 2 was compiled by Kaneshige and Shepherd[14], but was experimentally determined elsewhere[12,13,16,17].

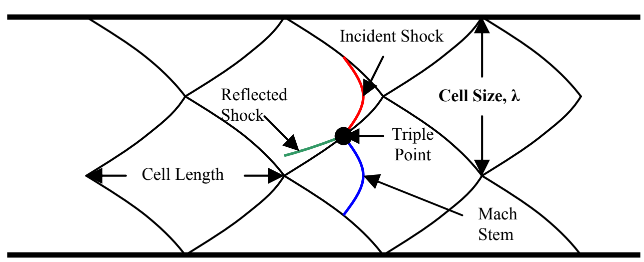


Figure 1. Drawing of representative two-dimensional detonation cell structure

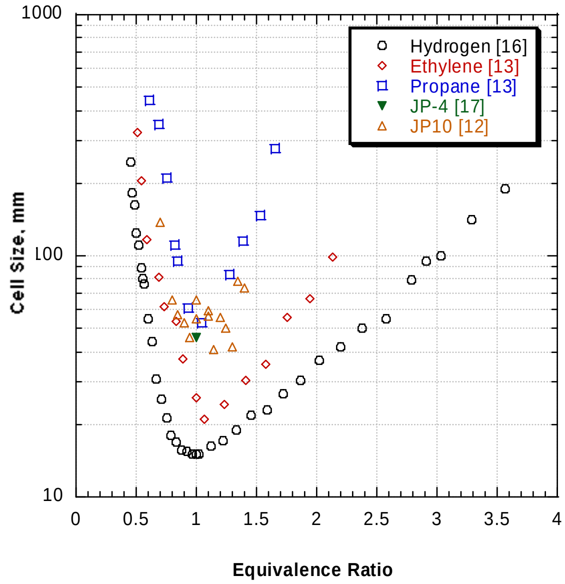


Figure 2. Plot of detonation cell size as a function of equivalence ratio for five different fuels.

Figure 3 is a plot of detonation cell size as a function of carbon number for mixtures of several straight chain hydrocarbons and hydrogen in air. As Fig. 3 demonstrates, once the carbon number reaches three (propane) there is little difference in detonation cell size. All for the hydrocarbons shown here with three or more carbon atoms have a cell between 40 and 50 mm. From Fig. 2 and Fig. 3, it is assumed that the heavy liquid hydrocarbons (avgas, JP-8, and S-8) will demonstrate similar performance to propane, and also that the larger straight chain hydrocarbons (butane through decane) will demonstrate similar performance to propane. The data from Fig. 3 was compiled by Kaneshige and Shepherd[14], but was experimentally determined elsewhere[13,14,16-18].

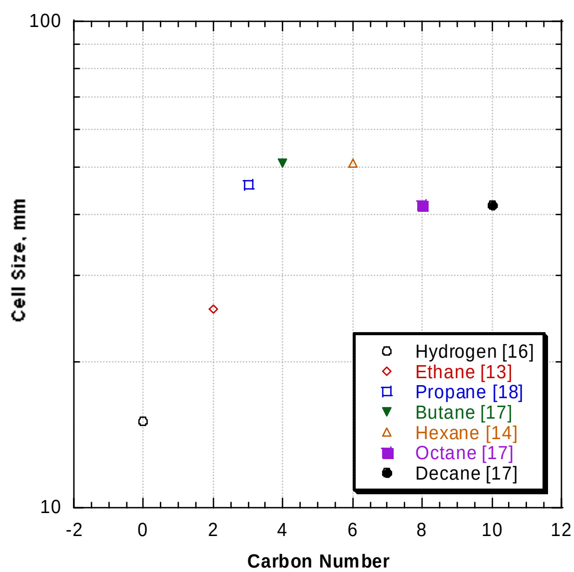


Figure 3. Plot of detonation cell size as a function of carbon number for seven different fuels.

Experimental Setup and Instrumentation

A. Facilities and PDE Specifics

This research was conducted in the Pulsed Detonation Research Facility (PDRF) located at Wright-Patterson AFB, Ohio. This facility was described in detail in other literature[20], and only the details relevant to this research are provided. The PDE for this research consisted of the valve train from a GM quad four engine head with two 2.44 meter long schedule 40 stainless steel detonation tubes (50.8 mm diameter), each with a 1.22 meter long Schelkin-like spiral, with one end adjacent to the closed end of the detonation tube, to promote DDT[21]. While testing JP-8 and S-8, the fuel was preheated to above 561 K (the threshold for complete fuel flash vaporization[22]) using a 38.1 cm long concentric counter-flow heat exchanger developed by Miser et al.[23].

The PDE cycle consisted of three equally timed phases. The three phases, in order, are the fill, fire, and purge, and are shown in Fig. 4. During the fill phase, the intake valves were opened filling the PDE detonation tube with a volume of premixed fuel and air equal to the volume of the detonation tube (fill fraction of one). For all tests the fill air was initially heated to 394 K prior to mixing with the fuel. During the fire phase, spark energy was released causing the formation of a deflagration wave that transitioned to a detonation wave. The ignition system provided spark pulses through modified spark plugs providing ignition energies of 115 mJ apiece. The spark delay after the intake valves closed was 4 msec. During the purge phase, the exhaust valves were opened filling the detonation tube with a volume of air (unheated) equal to half the volume of the detonation tube (purge fraction of 0.5). The purge air cooled the detonation tube and removed a portion of the exhaust gases from the detonation tube preventing auto-ignition. The PDE firing frequency was kept constant at 10 Hz for all testing.

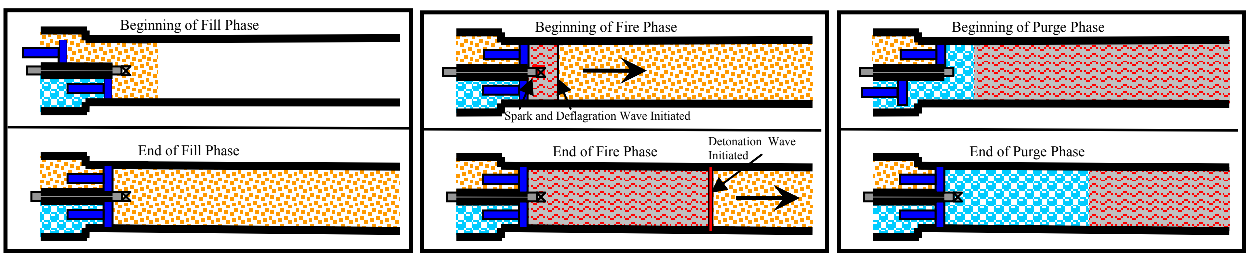


Figure 4. Diagrams of the fill, fire, and purge phases of the detonation cycle.

B. Fuel Deliver Systems

The hydrogen fuel supply is provided by a hydrogen tuber trailer located outside of the research facility, while ethylene is supplied via commercial tanks inside the test cell. The gaseous fuels are routed into the facility and through a dome loader and the critical flow nozzle. Gaseous fuel mass flow is regulated using the dome loader upstream of the critical flow nozzle. A surge tank is located downstream of the critical flow nozzle to prevent shock waves generated in the valve system from disrupting the flow at the critical flow nozzle. After traversing through the surge tank, the gaseous fuel was injected into the air stream.

The liquid fuel required for this testing was supplied by two hydraulic bladder accumulators, pressurized by nitrogen bottles. The nitrogen bottles pressurized the fuel above the critical pressure for the duration of the test to prevent boiling. The propane was supplied in commercials tanks, but was fed into the hydraulic bladder accumulators to maintain sufficient fuel pressure to prevent boiling. Once in the accumulators, propane was supplied to the PDE in the same manner as the other liquid fuels. For JP-8 and S-8, the fuel was pressure fed to the inlet of the heat exchanger. After traversing through the heat exchanger, the fuel was injected into the air stream. Avgas and propane were pressure fed directly into the air stream, bypassing the heat exchanger. A turbine flow meter, downstream of the accumulators, was used to measure fuel mass flow rate. Fuel mass flow rate of the fuel injection nozzles is proportional to the square root of the pressure drop across the fuel nozzles and fuel density[24,25]. To compensate for the decrease in fuel density during heating of the fuel in the supercritical regime, the charge pressure of the accumulators was increased to maintain a constant fuel mass flow rate. The accumulator charge pressure was varied during testing using a pneumatic dome [For details, see Ref. 26].

To minimize oxidative carbon deposition in the heat exchanger, the JP-8 was de-oxygenated through a nitrogen sparging process, reducing the oxygen concentration to less than 1 ppm. The sparging process involved bubbling a volume of nitrogen through the JP-8 to displace the trapped oxygen in the fuel. The volume of nitrogen necessary to reduce the oxygen concentration to acceptable levels was determined experimentally in previous work[27], and to ensure acceptable levels a factor of safety of two was applied to all nitrogen volume calculations.

C. Instrumentation

Ion probes were placed in ports, spaced 15.3 cm apart, along the length of the detonation and were used to measure the velocity of the combustion wave (wavespeed). Thermocouples were placed in the center of the flow path to gather temperature data at the inlet and outlet of the heat exchanger (J-type) to ensure proper flash vaporization. External heat exchanger wall temperatures were measured with J-type thermocouples mounted externally by compression clamps on the PDE detonation tube. A pressure transducer was situated at the closed end of the detonation tubes to measure the pressure, used to determine the ignition time.

D. Data Reduction

All combustion data was gathered on a dedicated computer employing a *LabVIEW* program named *OnLineWavespeed*. Using *OnLineWavespeed*, 12 channels of raw data (a spark traces, a head pressure traces, and 10 ion probe traces) were collected in 0.5 second intervals. The master scan rate was set at 1,000,000 scans per second, therefore 500,000 data points were gathered for each channel in 0.5 seconds. The output file also includes a curve fit to convert the binary values back into floating point. A C++ program was employed to convert the binary data into floating point using the curve fit saved with the data. The program then segments the data into separate firing cycles using the spark trace. Each spark trace denotes a new firing cycle.

Each firing cycle is then analyzed for ignition time information. The head pressure trace data is passed through a fourth-order, 401 point Savitzky-Golay digital finite-impulse response filter to reduce the high frequency noise[28]. Linear regression is then used to determine the slope of the pressure curve. A 1000 point window, beginning with the first 1000 points of the pressure trace, moves forward along the pressure trace until an average pressure rise of 5000 psi/sec is detected. The time in the center of the window is taken as the ignition time. Figure 5 is a plot of head pressure traces, after undergoing the Savitzky-Golay filter, for all six fuels. The pressure traces for all fuels, other than hydrogen, are shown with pressure offset (100 psi) for clarity. The hydrogen pressure rise is steeper than the other fuels, although ethylene demonstrates a pressure rise nearly as steep as hydrogen. Avgas, JP-8, and S-8 show similar pressure traces, however propane has the poorest pressure rise.

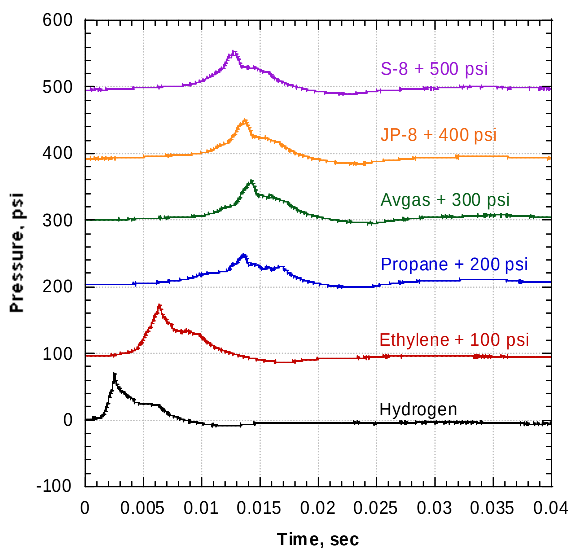


Figure 5. Head pressure traces for hydrogen, ethylene, Propane, avgas, JP-8, and S-8 with 100 psi offsets.

After the ignition time is determined, the probe times are calculated. The probe times are the time that the combustion wave crosses each of the ion probes. To determine the probe times, the C++ program takes an average of the first 1000 points of the ion probe traces to find a baseline value for the trace. The program then looks for the trace to drop below the baseline value for at least 500 consecutive data points. The probe time is the first point in the series of 500 points below the baseline value. This method essentially finds the corners of the ion probe trace and determines the time that they are found. Figure 6 is a plot of a sample pressure trace, along with a spark trace and ten ion probe traces.

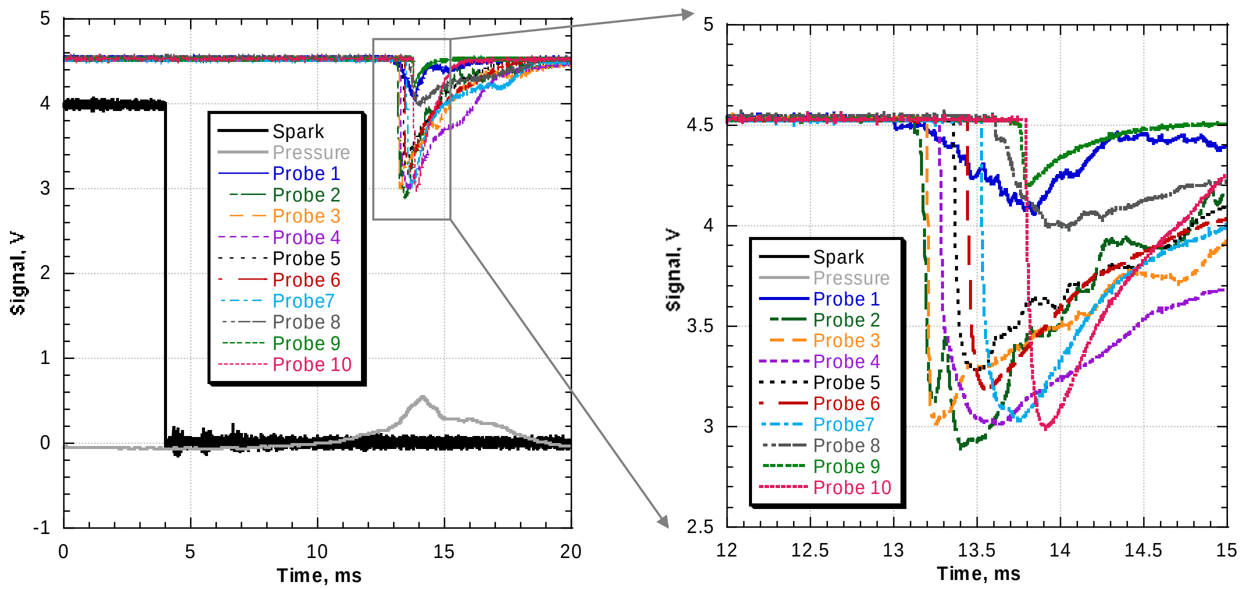


Figure 6. Representative output traces used to determine critical performance parameters.

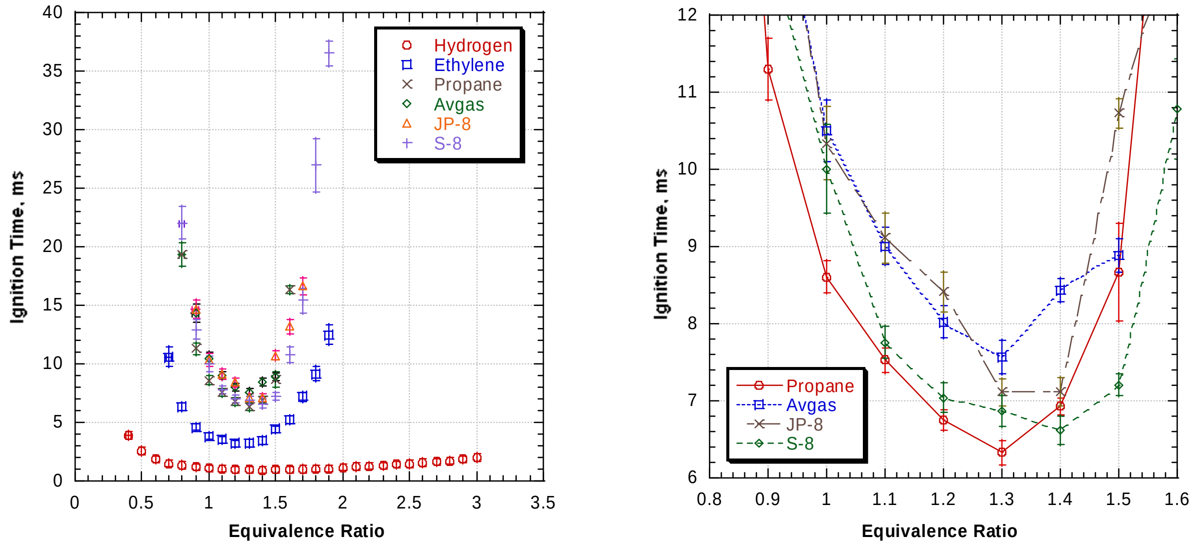
Once both the ignition times and probe times are found, they are inserted into an Excel spreadsheet. The spreadsheet first calculates the wavespeeds by dividing the difference in distance between two ion probes (15.3 cm for this effort) by the difference in the corresponding probe times. The spreadsheet then looks for wavespeeds above the CJ velocity. Once a wavespeed above the CJ limit is found, the program linearly interpolates between the wavespeed above the CJ wavespeed and the wavespeed at the location before it (below the CJ wavespeed) to determine the time and location where a wavespeed of exactly the CJ wavespeed occurs. The time and location found are the DDT time and the DDT distance, respectively. The wavespeed at 1.98 meters downstream of the engine is taken as the CJ wavespeed.

Results and Discussion

The experimentally determined ignition time, DDT time, DDT distance and CJ wavespeed as a function of equivalence ratio for mixtures of hydrogen, ethylene, propane, avgas, JP-8 and S-8 in air are presented. Each data point represents the mean value of 30 - 40 ignitions. The total experimental uncertainty is presented whenever possible. Schultz and Shepherd[19] used STANJAN to calculate theoretical CJ wavespeeds of hydrogen, ethylene, and propane. The experimental CJ wavespeed results from this research are compared to the theoretical CJ wavespeeds presented by Schultz and Shepherd[19]. The results are presented in tabular form in the appendix for reference.

A. Igntion Time

Figure 7(a) is a plot of ignition time as a function equivalence ratio for mixtures of hydrogen, ethylene, propane, avgas, JP-8, and S-8 in air. All six fuels reach a minimum ignition time near an equivalence ratio of 1.3. Hydrogen produces the largest flammability limits of all the fuels as well as the lowest ignition times for the entire range of equivalence ratio. The rich limit of hydrogen was not reached, because it was deemed unbeneficial to further increase the equivalence ratio. Ethylene produced the second largest flammability limits and the second lowest ignition times. The propane, avgas, JP-8, and S-8 ignition trends were so similar that the plot had to be zoomed in to compare them, Fig. 7(b). However, it can be seen in Fig. 7(a) that S-8 has larger flammability limits than JP-8 and avgas, due to S-8 typically containing fewer large hydrocarbons than JP-8 or avgas. Additionally, in Fig. 7(b) it is shown that S-8 demonstrates lower ignition times than JP-8 or avgas. Propane demonstrates the lowest ignition times on the liquid fed fuels, since it is a gas at ambient conditions, allowing for better mixing. The highest ignition times and smallest flammability limits are seen in avgas.

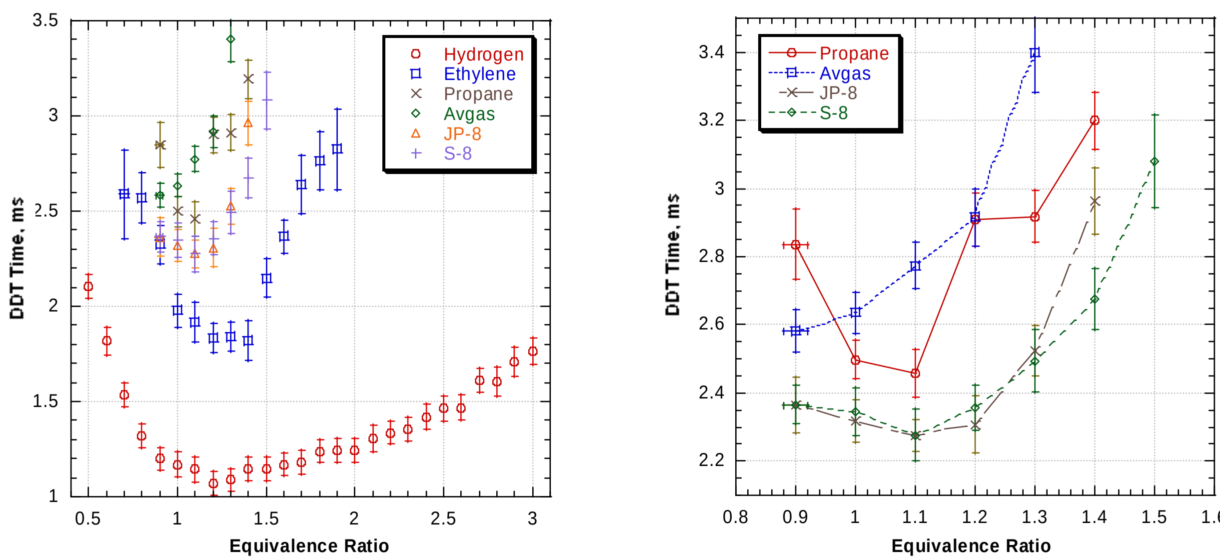


(a) (b)

Figure 7. Plots of ignition time as a function of equivalence ratio for mixtures of (a) hydrogen, ethylene, propane, avgas, JP-8, and S-8 in air and (b) propane, avgas, JP-8, and S-8 in air (zoomed in).

C. DDT Time

Figure 8(a) is a plot of DDT time as a function equivalence ratio for mixtures of hydrogen, ethylene, propane, avgas, JP-8, and S-8 in air. Except avgas, all of the fuels reach a minimum DDT time between an equivalence ratio of 1.1 and 1.2, which is lower than the point of minimum ignition time. The point of minimum DDT time for avgas is at the lean limit, 0.9. Hydrogen produces the largest detonatability limits of all the fuels as well as the lowest DDT times for the entire range of equivalence ratio. Again, the rich limit of hydrogen was not reach during this experiment. Ethylene produced the second largest detonability limits and the second lowest DDT times. The propane, avgas, JP-8, and S-8 detonation trends were so similar that the plot had to be zoomed in to compare them, Fig. 8(b). JP-8 and S-8 both demonstrate the lowest DDT times, except at the rich limits where S-8 has a lower DDT time than JP-8. JP-8 and S-8 (octane # ~ 40) outperform avgas and propane (octane # ~ 100) due to their lower octane number. Tucker et al.[7] showed that a higher octane number is indicative of poor detonability.



(a) (b)

Figure 8. Plots of DDT time as a function of equivalence ratio for mixtures of (a) hydrogen, ethylene, propane, avgas, JP-8, and S-8 in air and (b) propane, avgas, JP-8, and S-8 in air (zoomed in).

C. DDT Distance

Figure 9(a) is a plot of DDT distance as a function equivalence ratio for mixtures of hydrogen, ethylene, propane, avgas, JP-8, and S-8 in air. The same trends seen with DDT time appear in the DDT distance results. Detonability is ranked as follows: Hydrogen > Ethylene > S-8 ~ JP-8 > Propane > Avgas. Hydrogen detonates near 35 cm at a minimum, and ethylene detonates near 75 cm at a minimum. Again, the propane, avgas, JP-8, and S-8 detonation trends were so similar that the plot had to be zoomed in to compare them, Fig. 8(b). JP-8 and S-8 detonate in approximately the same distance, just less than one meter at a minimum. Propane detonates near 1.05 meters at a minimum, and avgas detonates near 1.1 meters at a minimum. Note: The trends from Fig 7(a), 8(a), and 9(a) follow the same as the trends of detonation cell size as a function of equivalence ratio, shown in Fig. 2.

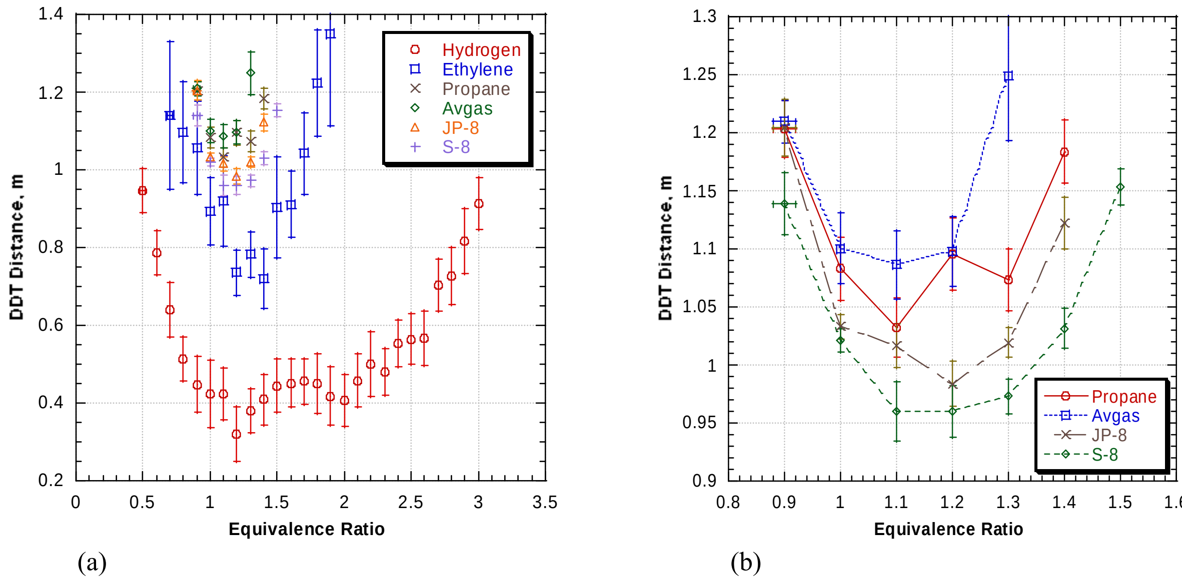
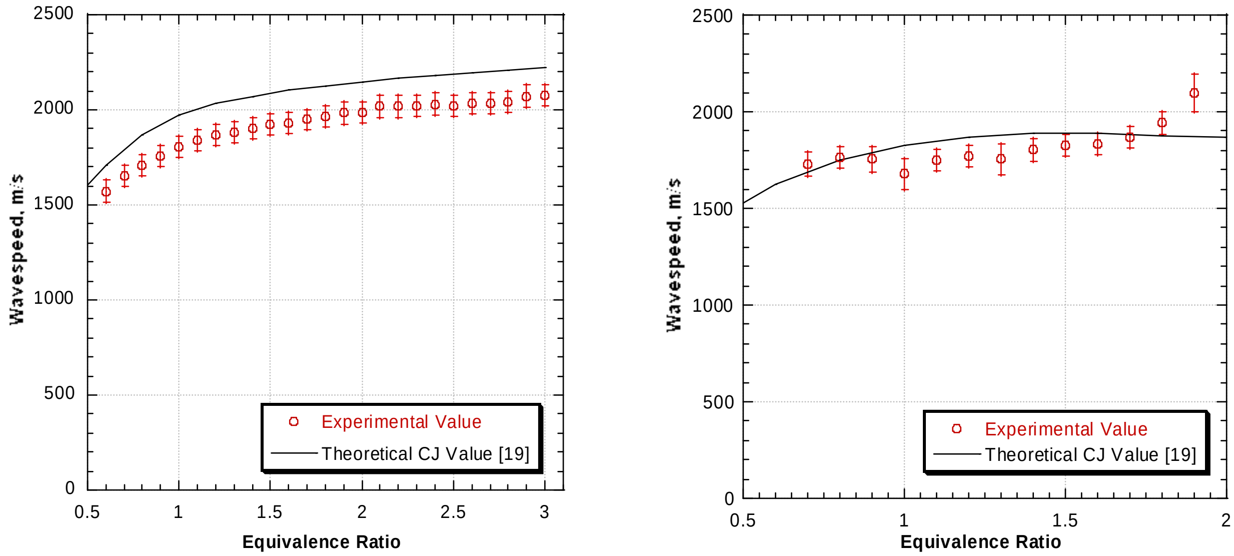


Figure 9. Plots of DDT time as a function of equivalence ratio for mixtures of (a) hydrogen, ethylene, propane, avgas, JP-8, and S-8 in air and (b) propane, avgas, JP-8, and S-8 in air (zoomed in).

D. Wavespeed

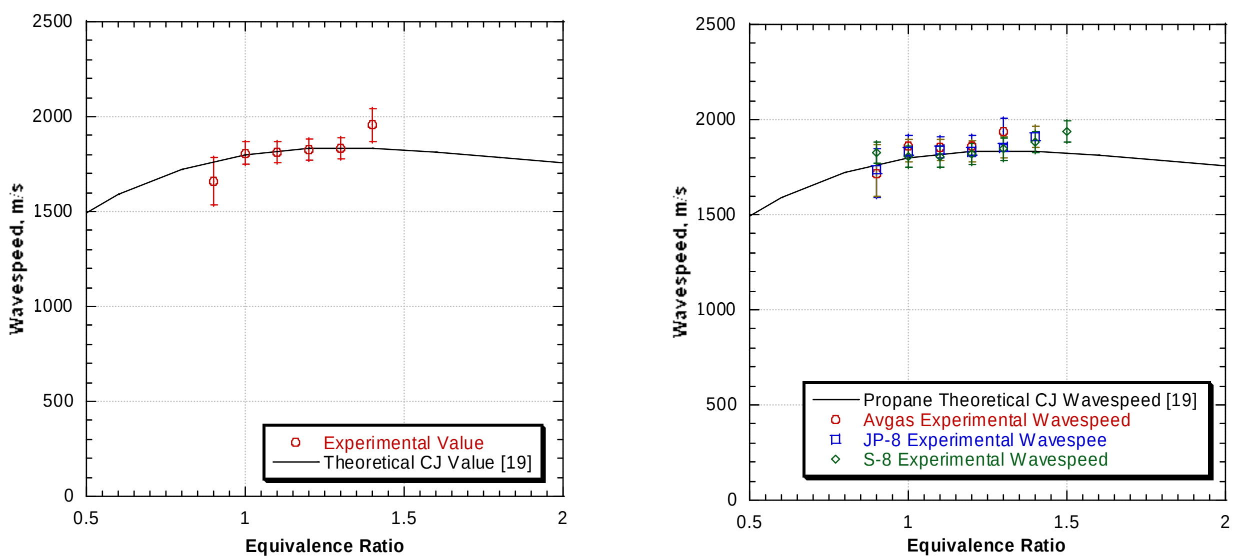
Figure 10 shows plots of wavespeed for mixtures of (a) hydrogen and (b) ethylene in air as a function of equivalence ratio. The experimental CJ wavespeeds of hydrogen are systematically between 6% and 8% lower than the theoretical CJ wavespeed. The wavespeed was measured approximately 33 cm from the open end of the detonation tube. Due to the high molecular diffusivity of hydrogen, the mixture was lean towards the open end of the detonation tube. The lean mixture resulted in lower than expected wavespeeds, as shown in Fig. 10(a). Wavespeed measurements of the hydrogen/air mixture taken farther upstream would have fallen within 5% of the theoretical CJ wavespeeds. The experimental CJ wavespeed of the ethylene/air mixture is within 5% of the theoretical values except at the rich limit. At the rich limit, the cell size for ethylene is near a 100 mm, which is twice the diameter of the tube. Due to the large cell size the detonation wave was unstable, resulting in an overdriven wavespeed.



(a) (b)

Figure 10. Plots of wavespeed as a function of equivalence ratio for mixtures of (a) hydrogen in air and (b) ethylene in air (compared to theoretical CJ wavespeeds).

Figure 11 shows plots of wavespeed for mixtures of (a) propane and (b) avgas, JP-8, and S-8 in air as a function of equivalence ratio. With the exception of the rich limit, all experimental CJ wavespeeds for the propane/air mixtures fell within 5% of the theoretical CJ wavespeeds. The cell size of propane at the rich limit is just over 100 mm, which led to an overdriven wavespeed. Since the cell size of avgas, JP-8, and S-8 are assumed to be similar to propane, the experimental CJ wavespeeds for avgas, JP-8, and S-8 are compared to the theoretical CJ wavespeeds for propane in Fig. 11(b). All of the experimental wavespeeds of avgas, JP-8, and S-8 fall within 5% of the theoretical CJ wavespeed for propane, further confirming the similarity in detonation characteristics between propane the these liquid hydrocarbons.



(a) (b)

Figure 11. Plots of wavespeed as a function of equivalence ratio for mixtures of (a) propane in air and (b) avgas, JP-8, and S-8 in air (compared to theoretical CJ wavespeeds for propane).

Conclusions

The ignition and detonability characteristics (ignition time, DDT time, DDT distance, and CJ wavespeed) have been determined for mixtures of hydrogen, ethylene, propane, avgas, JP-8, and S-8 in air. Hydrogen was found to have the best ignition and detonation characteristics, followed by ethylene. Propane, avgas, JP-8, and S-8 exhibited similar ignition and detonation characteristics, although JP-8 and S-8 demonstrated slightly lower DDT times and distances than avgas and propane. All ignition and detonation trends closely matched the cell size trends, further confirming the link between cell size and performance in a PDE. Minimum ignition times for all fuels occurred near an equivalence ratio of 1.3, while the minimum DDT times and distances occurred between equivalence ratios of 1.1 and 1.2. Experimental CJ wavespeeds were found to be within 5% of the theoretical CJ wavespeed for the majority of equivalence ratios with the exception of hydrogen, which was systematically between 6% and 8% lower than the theoretical value.

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Appendix: Results in Tabular Form

Table 1. Ignition time, DDT time, DDT Distance, and experimental CJ wavespeed for a hydrogen/air mixture

Equivalence Ratio	Ignition Time [ms]	DDT Time [ms]	DDT Distance [m]	CJ Wavespeed [m/s]
0.4	3.892	N/A	N/A	N/A
0.5	2.549	2.106	0.946	N/A
0.6	1.857	1.816	0.786	1573
0.7	1.503	1.534	0.641	1650
0.8	1.333	1.317	0.512	1710
0.9	1.202	1.198	0.448	1760
1	1.070	1.167	0.423	1806
1.1	1.048	1.143	0.424	1838
1.2	0.957	1.070	0.319	1868
1.3	0.952	1.087	0.379	1885
1.4	0.914	1.145	0.409	1904
1.5	0.965	1.146	0.444	1923
1.6	0.970	1.168	0.451	1933
1.7	1.012	1.179	0.456	1948
1.8	1.023	1.239	0.451	1968
1.9	1.059	1.242	0.418	1983
2	1.145	1.244	0.407	1986
2.1	1.225	1.305	0.457	2018
2.2	1.270	1.336	0.500	2020
2.3	1.316	1.355	0.481	2019
2.4	1.416	1.420	0.553	2031
2.5	1.461	1.464	0.565	2024
2.6	1.563	1.469	0.566	2036
2.7	1.625	1.611	0.705	2036
2.8	1.701	1.604	0.727	2043
2.9	1.849	1.712	0.817	2073
3	1.988	1.765	0.914	2075

Table 2. Ignition time, DDT time, DDT Distance, and experimental CJ wavespeed for an ethylene/air mixture

Equivalence Ratio	Ignition Time [ms]	DDT Time [ms]	DDT Distance [m]	CJ Wavespeed [m/s]
0.7	10.608	2.588	1.139	1728
0.8	6.355	2.568	1.097	1766
0.9	4.614	2.324	1.056	1754
1	3.831	1.977	0.894	1680
1.1	3.527	1.918	0.921	1751
1.2	3.200	1.836	0.735	1768
1.3	3.223	1.839	0.782	1754
1.4	3.446	1.817	0.720	1804
1.5	4.402	2.149	0.904	1825
1.6	5.244	2.366	0.912	1836
1.7	7.209	2.640	1.042	1871
1.8	9.152	2.765	1.225	1942
1.9	12.495	2.823	1.350	2097

Table 3. Ignition time, DDT time, DDT Distance, and experimental CJ wavespeed for a propane/air mixture

Equivalence Ratio	Ignition Time [ms]	DDT Time [ms]	DDT Distance [m]	CJ Wavespeed [m/s]
0.8	19.330	N/A	N/A	N/A
0.9	11.301	2.836	1.203	1659
1.0	8.608	2.499	1.083	1808
1.1	7.528	2.458	1.032	1811
1.2	6.750	2.908	1.095	1828
1.3	6.326	2.917	1.073	1831
1.4	6.926	3.199	1.184	1955
1.5	8.672	N/A	N/A	N/A
1.6	16.368	N/A	N/A	N/A

Table 4. Ignition time, DDT time, DDT Distance, and experimental CJ wavespeed for an avgas/air mixture

Equivalence Ratio	Ignition Time [ms]	DDT Time [ms]	DDT Distance [m]	CJ Wavespeed [m/s]
0.9	14.300	2.583	1.210	1717
1.0	10.502	2.636	1.101	1863
1.1	9.004	2.773	1.086	1854
1.2	8.024	2.916	1.098	1860
1.3	7.563	3.400	1.249	1936
1.4	8.430	N/A	N/A	N/A
1.5	8.884	N/A	N/A	N/A

Table 5. Ignition time, DDT time, DDT Distance, and experimental CJ wavespeed for a JP-8/air mixture

Equivalence Ratio	Ignition Time [ms]	DDT Time [ms]	DDT Distance [m]	CJ Wavespeed [m/s]
0.9	14.646	2.364	1.204	1734
1.0	10.337	2.318	1.033	1836
1.1	9.111	2.276	1.017	1837
1.2	8.411	2.307	0.984	1831
1.3	7.111	2.525	1.019	1854
1.4	7.118	2.964	1.122	1909
1.5	10.727	N/A	N/A	N/A
1.6	13.184	N/A	N/A	N/A
1.7	16.625	N/A	N/A	N/A

Table 6. Ignition time, DDT time, DDT Distance, and experimental CJ wavespeed for a S-8/air mixture

Equivalence Ratio	Ignition Time [ms]	DDT Time [ms]	DDT Distance [m]	CJ Wavespeed [m/s]
0.8	22.032	N/A	N/A	N/A
0.9	12.937	2.366	1.139	1826
1.0	10.006	2.346	1.021	1806
1.1	7.759	2.277	0.960	1805
1.2	7.038	2.357	0.960	1821
1.3	6.864	2.494	0.973	1844
1.4	6.614	2.676	1.031	1881
1.5	7.206	3.080	1.153	1939
1.6	10.783	N/A	N/A	N/A
1.7	15.431	N/A	N/A	N/A
1.8	26.975	N/A	N/A	N/A
1.9	36.534	N/A	N/A	N/A